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1 **LRH:** Budiharta, Slik, Raes, Meijaard, Erskine, and Wilson

2 **RRH:** MODELLING BIOMASS FOR BORNEAN FORESTS

3 **TITLE:** Estimating the Aboveground Biomass of Bornean Forest

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ABSTRACT

We apply a process-based model, called 3-PG (physiological principles for predicting growth), to estimate aboveground biomass for the primary forests of Borneo. Using publicly available soil and climate data, and parameterized with physiological traits of Bornean forest, the modelled aboveground biomass and basal area showed statistically significant relationships with field-measured data from 85 sites across four major forest types. Our results highlight the possibility to expand the application of 3-PG to forests of varying condition, which would facilitate inclusion of modelled forest biomass data for developing a Tier 3 carbon inventory system for Borneo.

Key words: Borneo; carbon accounting system; carbon sequestration; forest growth; forest type; process-based model.

TEXT

THE KYOTO PROTOCOL UNDER THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (UNFCCC) requires every signatory nation to standardise their carbon accounting systems (United Nations 1998). All 44 Annex 1 countries have submitted a National Inventory Report which contains a toolbox of methodologies for calculating sources and sinks of carbon (UNFCCC 2013). Non-Annex 1 countries are requested to submit a voluntary National Communication biennially, which outlines progress with the development of a carbon inventory system. Since 1999, only four non-Annex 1 countries (of 154 countries) have updated the third National Communication and only Mexico has completed the fourth and fifth reports (UNFCCC 2013).

Previous attempts to measure carbon dynamics associated with the tropical forests of SE Asia have mostly focused on regional quantification of stocks and losses generalised across forest types (Gibbs *et al.* 2007, Saatchi *et al.* 2011, Harris *et al.* 2012, Carlson *et al.* 2013, but see Berry *et al.* 2010), which could potentially fail to capture carbon gains at a local scale and thereby lead to the overestimation of net carbon emissions. These approaches would be classified as Tier 1 and Tier 2 due to the lower resolution of information associated with the stock change methods employed (IPCC 2006). Tier 3 approaches require detailed forest inventory data across a variety of forest types, complemented with region-specific process-based model(s), which have been field validated (IPCC 2006). To our knowledge, there have been no Tier 3 approaches trialled in SE Asia.

This study is the first application of a process-based model, 3-PG (physiological principles for predicting growth), to predict aboveground biomass (AGB) dynamics of the primary forests of Borneo. The 3-PG model estimates stand development based on physiological

processes that are simplifications of plant-environment interactions (Landsberg & Waring 1997). This model has been used for single-species plantations in temperate and sub-tropical regions (Landsberg & Sands 2011) and has resulted in accurate estimates of the growth of highly diverse forests in the Australian wet tropics and Amazon (White *et al.* 2006, Nightingale *et al.* 2008). We aim to apply the 3-PG model to obtain baseline estimates of the upper limits of AGB accumulation for the tropical forests of Borneo. We evaluate the performance of the model, and appraise the utility of the approach for developing a Tier 3 carbon accounting system for Borneo.

MODEL DESCRIPTION.—The 3-PG is a process-based model, which calculates forest productivity from absorbed photosynthetically active radiation and canopy quantum efficiency, constrained by atmospheric vapour pressure deficit, soil characteristics, and temperature (Landsberg & Waring 1997). The model consists of five biological sub-models for estimating biomass production, biomass allocation, stem stocking and mortality, soil and water balance, and stand management (Nightingale 2005). A detailed description of the model is presented by Landsberg & Sands (2011). The inputs into the 3-PG model include soil and climate data, and field-measured data are required for model validation. Estimates of variables pertaining to forest growth (including biomass and stand basal area) are predicted on a monthly and annual basis for up to 120 years.

FIELD-MEASURED DATA.—Empirical data on the biomass and basal area of primary forest was obtained from 85 sites across Borneo (Slik *et al.* 2010 and additional sources: Appendix S1), along with the geographical coordinates and elevation for each site. The site data were differentiated into four major forest types: lowland forest (n=62), montane forest (n=7), heath

forest (n=9), and peat swamp forest (n=7) (Wikramanayake *et al.* 2002, Raes 2009). Slik *et al.* (2010) found no spatial autocorrelation among the same sampled sites.

SOIL AND CLIMATIC DATA.—Data on soil properties were generated from the Harmonized World Soil Database, including soil texture class, maximum and minimum plant available soil water, and fertility ratings (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). Soil texture was categorized into four soil classes: clay; clay loam; sandy loam; and sand. Plant available soil water was obtained from the available water storage capacity, and classified into seven classes, ranging from 0 to 150 mm/m. The fertility rating was assigned based on the percentage of organic carbon, which was standardised between zero and one. We assume that the modus organic carbon value (equating to 1%) associated with the mineral soils of tropical regions corresponds to a soil fertility rating of 0.2 (Nightingale *et al.* 2008). Considering the high organic content but low available nutrients of peat soil, a uniform fertility rating of 0.19 was assigned, which is similar to the average rating attributed to the similarly infertile soil of heath forest (Cannon & Leighton 2004).

Four climate input variables, including solar radiation, temperature, precipitation and vapour pressure deficit were obtained from a number of sources. Daily solar radiation data (MJ/m/d) was acquired from the monthly averages of earth surface insolation incidence from 22 years of satellite observation (NASA 2013). Monthly maximum, mean and minimum temperature (°C), as well as monthly precipitation (mm/mo) were derived from the WORLDCLIM database (Hijmans *et al.* 2005). A comprehensive vapour pressure deficit dataset does not exist for Borneo, therefore the inputs for this variable (mBar) were generated from the

WORLDCLIM database and computed as 0.62 times the difference between the saturated vapour pressure at the maximum and minimum temperatures (Waring 2013).

PARAMETERIZATION OF THE 3-PG MODEL.—We estimated stand development starting from the commencement of forest succession, assuming that there are tree seedlings present and vegetation regenerates passively (White *et al.* 2000, White *et al.* 2006). The 3-PG model was originally developed for monoculture plantations with parameters describing allometric relationships, canopy conductance and canopy structure assigned in the context of a single species. As our sample sites comprise a diversity of species, we assigned parameters specific to tropical forest based on studies conducted on the island of Borneo or elsewhere in the tropics and used default values where more detailed data could not be located (Table S1). The outputs are highly sensitive to the canopy quantum efficiency parameter (Nightingale *et al.* 2008) and therefore a range of values were (Table S1) representing the three groups of plant functional traits (i.e. fast growing pioneer, fast growing dipterocarp and slow growing dipterocarp) and three canopy layers (i.e. understorey, main canopy and emergent) that are representative of Bornean forest (Eschenbach *et al.* 1998, Huth & Ditzer 2000). We determined the optimum temperature for growth for each sampled site using climate data following Nightingale *et al.* (2008) with formulation adapted from Waring (2013) (Equation 1).

$$T_{opt} = [(T_{max} - T_{min}) \times 0.6] + T_{min} \quad (\text{Equation 1})$$

We iteratively ran the model and subsequently matched the modelled outputs to field-measured data to optimise the value of canopy quantum efficiency for each site (Landsberg *et al.* 2003, Nightingale *et al.* 2008).

COMPARISON OF MODELLED AND FIELD-MEASURED DATA.—We employed regression analysis to assess the relationships between the modelled and field-measured AGB using R Statistical Software (R v. 3.0.1, R Development Core Team 2013).

RESULTS.—The 3-PG model accurately predicted AGB compared to ground-based estimates of 85 sites ($R^2 = 0.958$; $P < 0.001$) with SE of 25.9 Mg dry mass/ha (Fig. 1) and also provided strong predictions of basal area ($R^2 = 0.774$; $P < 0.001$; SE = 3.37 m²/ha). Higher residual error was observed at sampled sites with the lowest and highest basal area, which is likely the result of inaccurate allometric parameterization (Fig. 1).

AGB is not uniformly distributed across forest types, with lowland forest having the highest stock on average, reaching 477 Mg/ha, and heath forest predicted to have approximately 70% of this stock (Table S2). In general, 3-PG was able to estimate the AGB of the four major forest types ($R^2 > 0.8$), with the model tending toward overestimation (Table S2 and Fig. S1).

The modelled forest growth follows a logistic curve with the rate of predicted AGB accumulation greatest in the first 20-30 years and reaching a steady state at around 60-70 years (Fig. 2). On average, by 20 years, Bornean forest could accumulate 156 Mg/ha with the greatest variation of growth exhibited by montane forest, which is driven by the high climate variability (i.e. monthly temperature and precipitation) across the sampled sites for this forest type.

DISCUSSION.—Our study is the first application of 3-PG to multiple forest types on the island of Borneo, representing further expansion of 3-PG to multi-species and multi-age vegetation tropical forests (White *et al.* 2006, Nightingale *et al.* 2008). Despite its simplicity, the 3-PG model accurately predicted forest growth, particularly AGB (Figs. 1 and S1). The modelled AGB over 100 years of simulation approximates the upper limits of AGB accumulation. Forests continue to accumulate AGB beyond this period although the net accumulation is minimal due to stand mortality and decelerating primary productivity after reaching a mature successional state (Brown & Lugo 1990, Guariguata & Ostertag 2001). It is therefore likely that AGB is overestimated in our predictions.

Using a statistical model, Slik *et al.* (2010) found that annual precipitation, soil fertility and soil drainage determine the distribution of AGB across Borneo. As would be anticipated, we find that sites occurring on fertile soil (e.g. in lowland and montane forests) accumulate higher AGB than those on poor soil (e.g. in heath and peat swamp forests). Aside from environmental factors, vegetation intrinsic traits also affect AGB accumulation. The canopy quantum efficiency resembles the rate of photosynthesis of a plant as a response to absorbed light by the canopy (Eschenbach *et al.* 1998). The range for this parameter used in this study (i.e. 0.023-0.043 mol C/mol photons) is higher than that used for application of 3-PG to the forests of tropical Australia (i.e. 0.013-0.0175 mol C/mol photons), resulting in higher average AGB (i.e. 382 Mg/ha for Borneo compared to 257 Mg/ha for the tropical forests in Australia) (Nightingale *et al.* 2008). Using 3-PG model, the accumulation of AGB in the Brazilian Amazon after 20 years has been predicted to be approximately 102 Mg/ha (White *et al.* 2006). The higher value of modelled AGB of Bornean forest in this study (i.e. 156 Mg/ha after 20 years), reflects the overall higher biomass carrying capacity of Bornean forests (Slik *et al.* 2010).

1 The primary advantage of 3-PG compared to other tropical forest growth models is the
2 simplification of physiological processes into mathematical equations without necessarily
3 requiring a large amount of environmental data and input parameters (Landsberg & Waring
4 1997, Nightingale *et al.* 2004). This is particularly relevant to data-poor regions such as Borneo
5 where long-term and comprehensive climate data are generally lacking. We show that even using
6 publicly available climate and soil data, 3-PG performs well in predicting AGB in highly diverse
7 Bornean forest.

8 A technical limitation of the 3-PG model is a lack of transparent and objective means to
9 assign the soil fertility rating (Landsberg & Sands 2011). In many applications of 3-PG, the
10 fertility rating is determined arbitrarily through expert judgement (White *et al.* 2000, White *et al.*
11 2006, Nightingale *et al.* 2008). In this study, we attempted to reduce this subjectivity by using
12 organic carbon as a surrogate, although this approach does not account for the influence of the
13 availability of phosphorus, potassium, and magnesium or soil acidity on the fertility of Bornean
14 soils (Paoli *et al.* 2008). The limited amount of available inventory data for primary forests to
15 validate the model, in addition to the variation in sample sizes across forest types, impacts the
16 reliability of the predictions we present. Furthermore, the lack of inventory data precludes the
17 systematic analysis of forest biomass across a variety of disturbance histories (e.g. logged and
18 burnt forest) and degradation conditions, which is required to deliver a comprehensive Tier 3
19 carbon accounting systems (IPCC 2006).

20 We have demonstrated the application of a simple, yet robust, process-based model to
21 estimate forest biomass, revealing the potential to accurately predict the upper limits of biomass
22 accumulation for the major forest types occurring on the island of Borneo. Our research is the
23 first step towards the integration of a process-based model into a Tier 3 carbon accounting

1 system for the three nations of Borneo, which would support the implementation of climate
2 policies and associated REDD+ projects. In the future, a standardized forest inventory
3 methodology for Borneo with sampling distributed across forest types and within stands of
4 varying forest condition would improve the accuracy and utility of the biomass predictions
5 presented here.

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9
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1 **FIGURES LEGENDS**

2

3 FIGURE 1. Comparison between the 3-PG modelled (over 100 years) and field-measured data of
4 AGB (Mg/ha) and basal area (m^2/ha) across Borneo. The straight line indicates 1:1 line.

5

6 FIGURE 2. Predicted AGB (Mg/ha) accumulation over 100 years for each forest type: (A)
7 lowland forest; (B) montane forest; (C) heath forest; and (D) peat swamp forest. Solid line is the
8 average AGB modelled for each forest type; dashed lines are the upper and lower confidence
9 intervals.

FIGURES

FIGURE 1

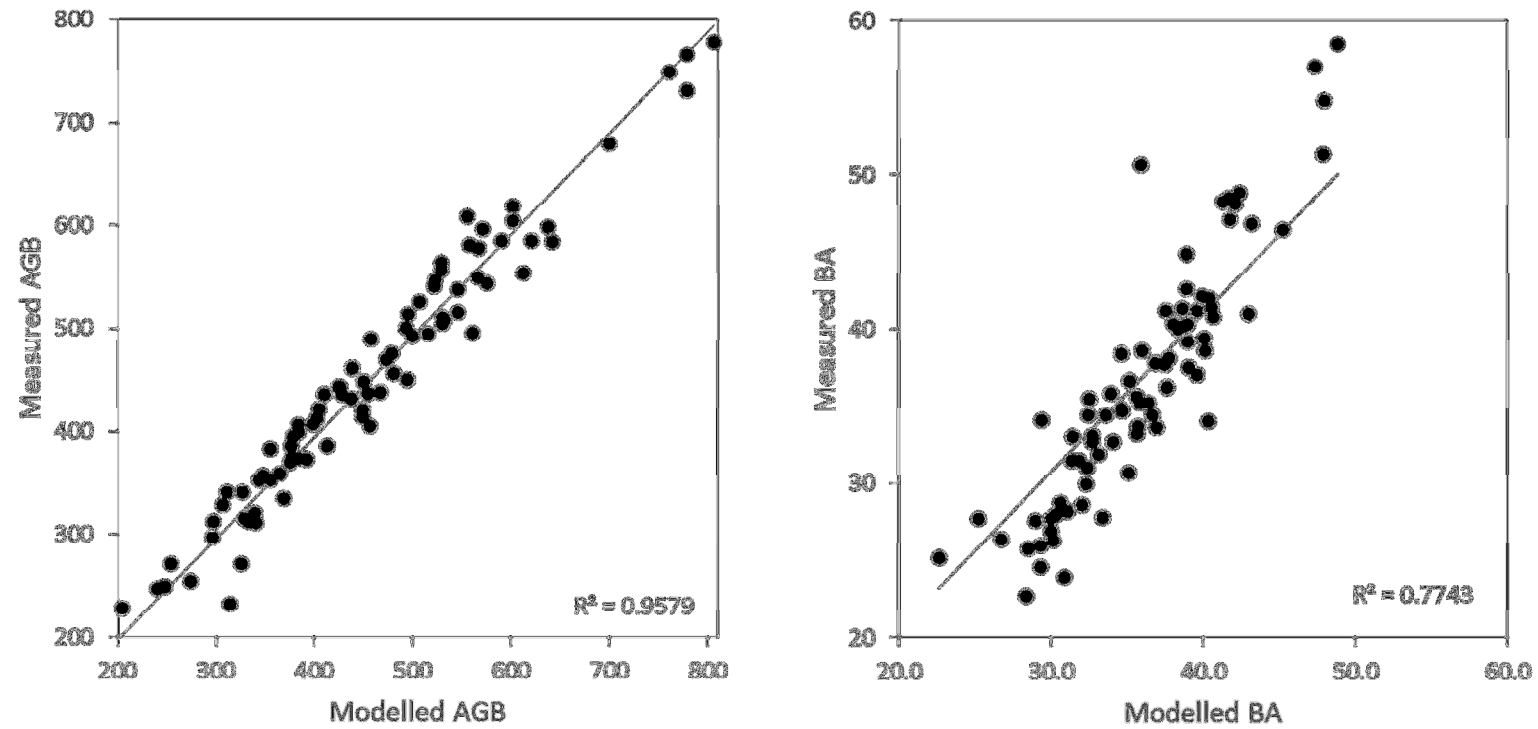
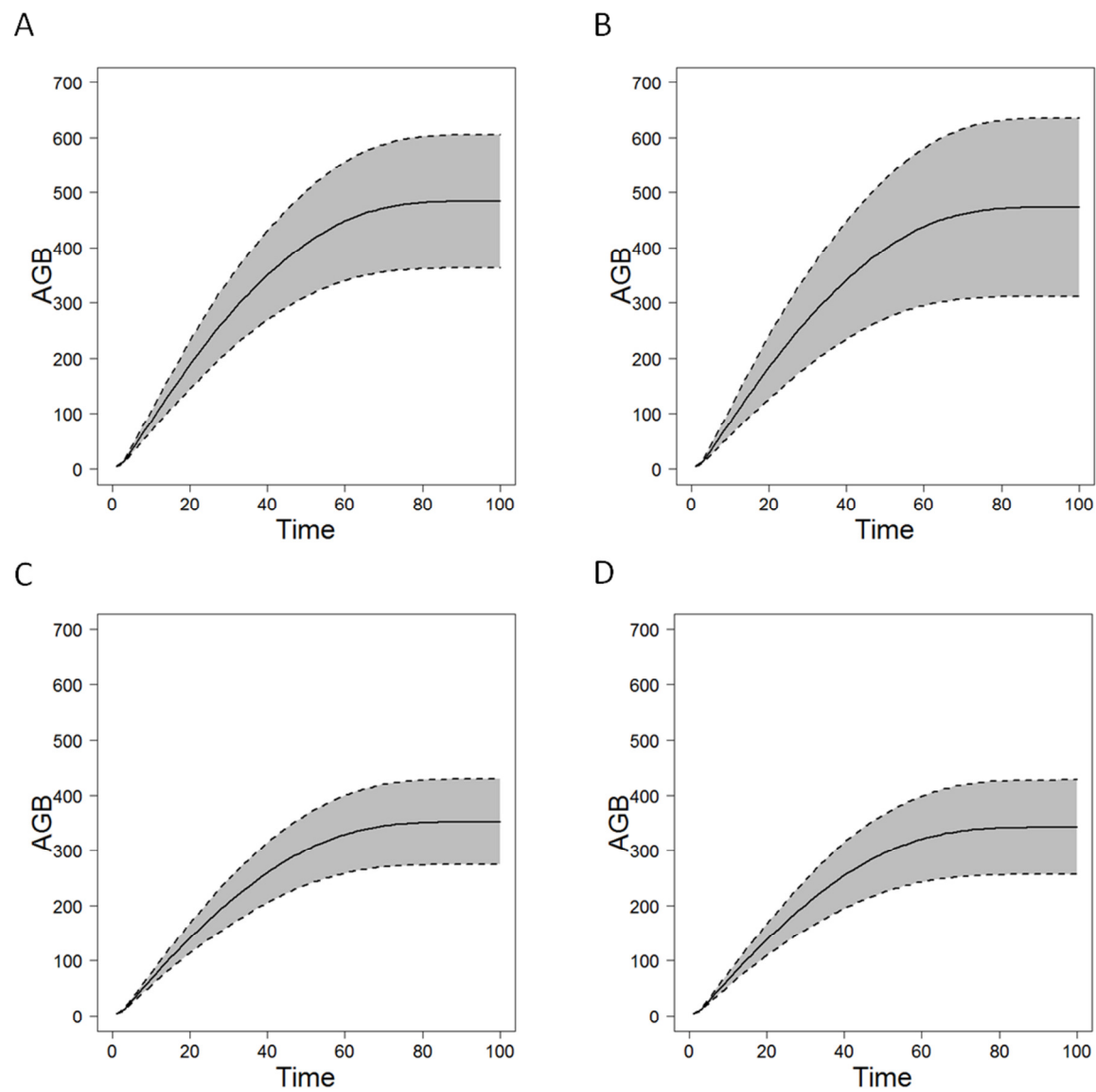


FIGURE 2



SUPPORTING INFORMATION

APPENDIX S1. List of additional field-measured data

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TABLE S1. List of parameter values included in the 3-PG simulation.

Parameter	Value	Source
Foliage – stem partitioning ratio	1	Clearwater <i>et al.</i> (1999)
Stem mass v. diameter relationships	2.6	Slik <i>et al.</i> (2010)
Minimum temperature for growth	Site specific	Hijmans <i>et al.</i> (2005)
Maximum temperature for growth	Site specific	Hijmans <i>et al.</i> (2005)
Maximum stand age in age modifier	100 yrs	Brown & Lugo (1990); Silver <i>et al.</i> (2000); White <i>et al.</i> (2006)
Maximum litter fall rate	0.04/mo	Paoli & Curran (2007)
Age at median litter fall rate	24 mo	White <i>et al.</i> (2006)
Maximum canopy conductance	0.019 m/s	Kumagai <i>et al.</i> (2004)
Leaf area index for maximum conductance	6.2	Kumagai <i>et al.</i> (2004)
Stomatal response to VPD	0.04/mBar	Clearwater <i>et al.</i> (1999)
Self-thinning rule	2	Slik <i>et al.</i> (2010)
Canopy quantum efficiency	0.023-0.043 mol C/mol photons	Eschenbach <i>et al.</i> (1998); Huth & Ditzer (2000)
Specific leaf area at age 0	6 m ² /kg	Breareley <i>et al.</i> (2003)
Specific leaf area for mature leaves	6 m ² /kg	Breareley <i>et al.</i> (2003)

Literature sources for parameterization

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TABLE S2. Summary of measured and modelled AGB in Mg/ha after stratification according to forest type. The values in brackets are the standard deviation of the mean.

	Lowland forest	Montane forest	Heath forest	Peat swamp forest
Average measured AGB	477.0 (117.0)	461.9 (157.3)	342.7 (82.2)	348.7 (81.8)
Average modelled AGB	484.3 (120.5)	473.6 (150.0)	352.1 (77.5)	348.5 (88.9)

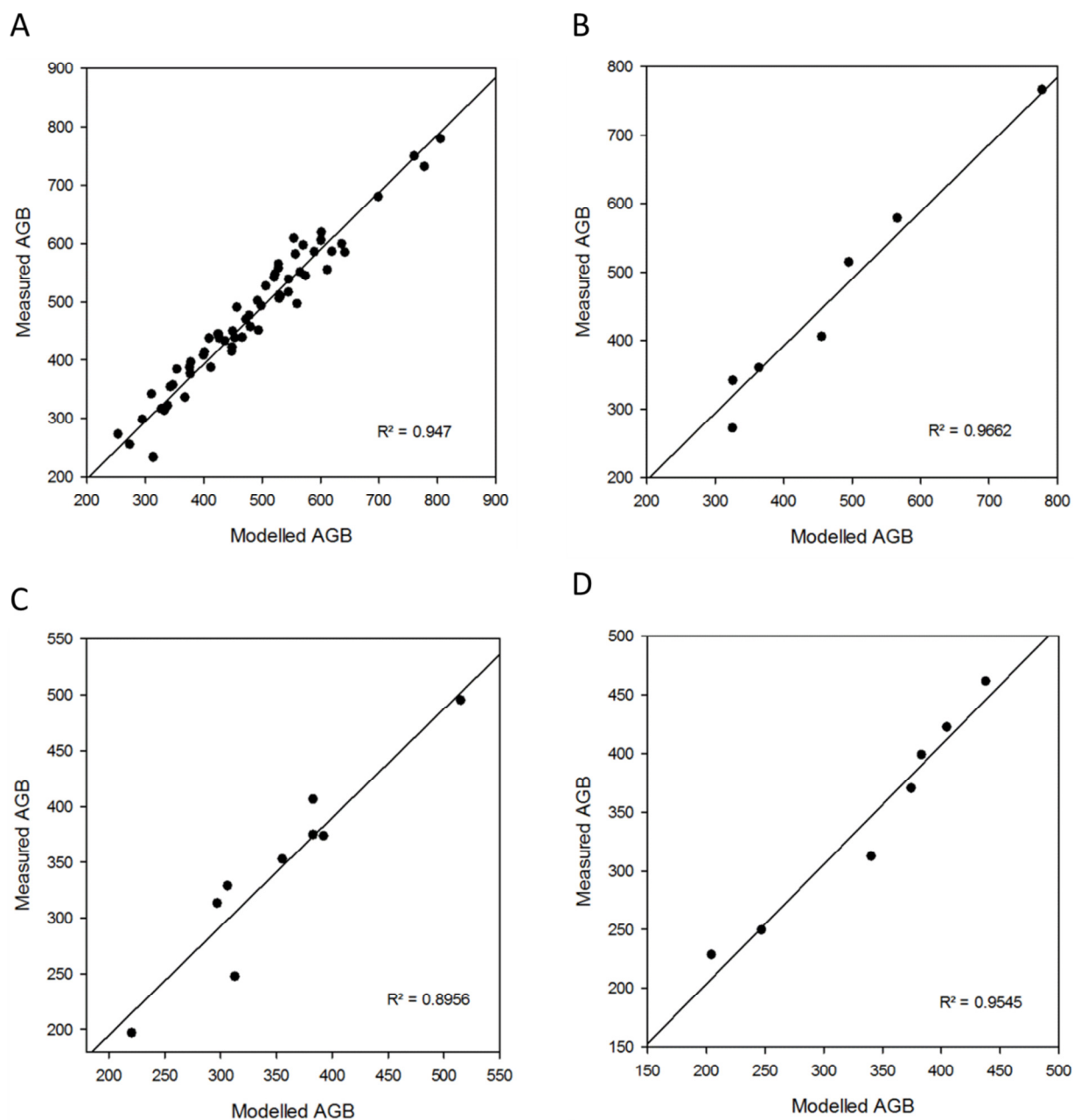


FIGURE S1. Comparison between the 3-PG modelled (over 100 years) and field-measured data of AGB (Mg/ha) for each forest type: (A) lowland forest; (B) montane forest; (C) heath forest; and (D) peat swamp forest. The straight line indicates 1:1 line.